



# Search for supersymmetry in $pp$ collisions at $\sqrt{s} = 7$ TeV in final states with missing transverse momentum and $b$ -jets<sup>☆</sup>

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## ABSTRACT

Results are presented of a search for supersymmetric particles in events with large missing transverse momentum and at least one heavy flavour jet candidate in  $\sqrt{s} = 7$  TeV proton–proton collisions. In a data sample corresponding to an integrated luminosity of  $35 \text{ pb}^{-1}$  recorded by the ATLAS experiment at the Large Hadron Collider, no significant excess is observed with respect to the prediction for Standard Model processes. For  $R$ -parity conserving models in which sbottoms (stops) are the only squarks to appear in the gluino decay cascade, gluino masses below 590 GeV (520 GeV) are excluded at the 95% C.L. The results are also interpreted in an MSUGRA/CMSSM supersymmetry breaking scenario with  $\tan\beta = 40$  and in an  $SO(10)$  model framework.

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## 1. Introduction

Supersymmetry (SUSY) [1] is one of the most compelling theories to describe physics beyond the Standard Model (SM). It naturally solves the hierarchy problem and provides a possible candidate for dark matter. SUSY is a symmetry that relates fermionic and bosonic degrees of freedom, and postulates the existence of superpartners for the SM particles. Experimental data imply that supersymmetry is broken and that the superpartners are expected to be heavier than the SM partners. In the framework of a generic  $R$ -parity conserving minimal supersymmetric extension of the SM, the MSSM [2], SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. In a large variety of models, the LSP is the lightest neutralino,  $\tilde{\chi}_1^0$ , which is only weakly interacting.

If supersymmetric particles exist at the TeV energy scale, the coloured superpartners of quarks and gluons, the squarks ( $\tilde{q}$ ) and gluinos ( $\tilde{g}$ ), are expected to be copiously produced via the strong interaction at the Large Hadron Collider (LHC) [3,4]. Their decays via cascades ending with the LSP produce striking experimental signatures leading to final states containing multi-jets, missing transverse momentum (its magnitude is referred to as  $E_T^{\text{miss}}$  in the following) – resulting from the undetected neutralinos – and possibly leptons. First searches for the production of SUSY particles at the LHC have been published recently [5–7].

In the MSSM, the scalar partners of right-handed and left-handed quarks,  $\tilde{q}_R$  and  $\tilde{q}_L$ , can mix to form two mass eigenstates. These mixing effects are proportional to the corresponding fermion masses and therefore become important for the third generation. In particular, large mixing can yield sbottom ( $\tilde{b}_1$ ) and stop ( $\tilde{t}_1$ ) mass eigenstates which are significantly lighter than other squarks. Consequently,  $\tilde{b}_1$  and  $\tilde{t}_1$  could be produced with large cross sections at the LHC, either via direct pair production or, if kinematically allowed, through  $\tilde{g}\tilde{g}$  production with subsequent  $\tilde{g} \rightarrow \tilde{b}_1 b$  or  $\tilde{g} \rightarrow \tilde{t}_1 t$  decays. Depending on the SUSY particle mass spectrum, the cascade decays of gluino-mediated and pair-produced sbottoms or stops result in complex final states consisting of  $E_T^{\text{miss}}$ , several jets, among which  $b$ -quark jets ( $b$ -jets) are expected, and possibly leptons.

In this Letter, a search for final states involving  $E_T^{\text{miss}}$  and  $b$ -quark jets is discussed. Results on searches for direct sbottom [8, 9], stop [10,11] and gluino mediated production [12] have been previously reported by the Tevatron experiments, placing exclusion limits on the mass of these particles in several MSSM scenarios.

The search described here is based on  $pp$  collision data at a centre-of-mass energy of 7 TeV recorded by the ATLAS experiment at the LHC in 2010. The total data set corresponds to an integrated luminosity of  $35 \text{ pb}^{-1}$  [13]. To enhance the sensitivity to different SUSY models, the search was performed using two mutually exclusive final states, characterised by the presence of leptons. They are referred to as zero-lepton and one-lepton analyses in the following.

In the zero-lepton analysis, events are required to contain energetic jets, of which one must be identified as a  $b$ -jet, large  $E_T^{\text{miss}}$  and no isolated leptons ( $e$  or  $\mu$ ). The zero-lepton analysis

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is employed to search for gluinos and sbottoms in MSSM scenarios where the  $\tilde{b}_1$  is the lightest squark, all other squarks are heavier than the gluino, and  $m_{\tilde{g}} > m_{\tilde{b}_1} > m_{\tilde{\chi}_1^0}$ , such that the branching ratio for  $\tilde{g} \rightarrow \tilde{b}_1 b$  decays is 100%. Sbottoms are produced via gluino-mediated processes or via direct pair production. They are assumed to decay exclusively via  $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$ , where  $m_{\tilde{\chi}_1^0}$  is assumed to be 60 GeV, above the present exclusion limit [14].

In the one-lepton analysis, events are required to contain energetic jets, of which one must be identified as a  $b$ -jet, large  $E_T^{\text{miss}}$  and at least one high- $p_T$  electron or muon. This analysis is sensitive to SUSY scenarios in which the stop is the lightest squark and  $m_{\tilde{g}} > m_{\tilde{t}_1}$ . If the stop decay channel  $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm$  dominates, possible subsequent  $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l^\pm \nu$  decays result in experimental signatures with energetic charged leptons in addition to  $b$ -jets and  $E_T^{\text{miss}}$ . In the present analysis, only  $\tilde{g}\tilde{g}$  and  $\tilde{t}_1\tilde{t}_1$  pair production are considered, with 100% branching ratios for the  $\tilde{g} \rightarrow \tilde{t}_1 t$  and  $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm$  decays. The chargino is assumed to have a mass  $m_{\tilde{\chi}_1^\pm} \simeq 2 \cdot m_{\tilde{\chi}_1^0}$ , with  $m_{\tilde{\chi}_1^0} = 60$  GeV, and to decay through a virtual  $W$  boson ( $\text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l^\pm \nu) = 11\%$ ).

In addition to the aforementioned phenomenological MSSM models, the results are interpreted in the framework of minimal supergravity (MSUGRA/CMSSM [15]) and in specific Grand Unification Theories (GUTs) based on the gauge group  $\text{SO}(10)$  [16]. For MSUGRA/CMSSM, limits on the universal scalar and gaugino mass parameters ( $m_0, m_{1/2}$ ) are presented for fixed values of the ratio of the Higgs vacuum expectation value,  $\tan\beta = 40$ , the common trilinear coupling at the GUT scale  $A_0 = 0$  GeV (–500 GeV), and the sign of the Higgsino mixing parameter  $\mu > 0$ . Taking large values of  $\tan\beta$  or negative values of  $A_0$  with other model parameters held fixed leads to lower third generation sparticle masses compared to those of the other sparticles. Depending on  $m_0$  and  $m_{1/2}$ , any of the final states such as  $\tilde{q}\tilde{q}$ ,  $\tilde{q}\tilde{g}$  and  $\tilde{g}\tilde{g}$  might be dominant. In the  $\text{SO}(10)$  scenario, the SUSY particle mass spectrum is characterised by the low masses of the gluinos (300–600 GeV), charginos (100–180 GeV) and neutralinos (50–90 GeV), whereas all scalar particles have masses beyond the TeV scale. Depending on the sparticle masses, chargino–neutralino and gluino–pair production dominate. The three-body gluino decays  $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$  and  $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_2^0$  are expected to lead to final states with high  $b$ -jet multiplicities. Two specific models are considered [17], the D-term splitting model, DR3, and the Higgs splitting model, HS.

## 2. The ATLAS detector

The ATLAS detector [18] comprises an inner detector surrounded by a thin superconducting solenoid, and a calorimeter system. Outside the calorimeters is an extensive muon spectrometer in a toroidal magnetic field.

The inner detector system is immersed in a 2 T axial magnetic field and provides tracking information for charged particles in a pseudorapidity range  $|\eta| < 2.5$ .<sup>1</sup> The highest granularity is achieved around the vertex region using silicon pixel and microstrip detectors. These detectors allow for an efficient tagging of jets originating from  $b$ -quark decays using impact parameter measurements and the reconstruction of secondary decay vertices. The transition radiation tracker, which surrounds the silicon detectors, contributes to track reconstruction up to  $|\eta| = 2.0$  and improves the electron identification by the detection of transition radiation.

The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . The highly segmented electromagnetic calorimeter consists of lead absorbers with liquid argon as the active material and covers the pseudorapidity range  $|\eta| < 3.2$ . In the region  $|\eta| < 1.8$ , a presampler detector consisting of a thin layer of liquid argon is used to correct for the energy lost by electrons, positrons, and photons upstream of the calorimeter. The hadronic tile calorimeter is a steel/scintillating-tile detector and is placed directly outside the envelope of the electromagnetic calorimeter. In the forward regions, it is complemented by two end-cap calorimeters using liquid argon as active material and copper or tungsten as absorber material.

Muon detection is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets, instrumented with separate trigger and high-precision tracking chambers. A system of three toroids, a barrel and two end-caps, generates the magnetic field for the muon spectrometer in the pseudorapidity range  $|\eta| < 2.7$ .

## 3. Simulated event samples

Simulated event samples were used to determine the detector acceptance, the reconstruction efficiencies and the expected event yields for signal and background processes.

SUSY signal processes were generated for various models using the HERWIG++ [19] v2.4.2 Monte Carlo program. The particle mass spectra and decay modes were determined using the ISASUSY from ISAJET [20] v7.80 and SUSYHIT [21] v1.3 programs. The latter was used for the assumed MSSM scenarios, which are parametrised in the  $(m_{\tilde{g}}, m_{\tilde{b}_1})$  and  $(m_{\tilde{g}}, m_{\tilde{t}_1})$  planes, with gluino masses above 300 GeV. The SUSY sample yields were normalised to the results of next-to-leading order (NLO) calculations, as obtained using the PROSPINO [22] v2.1 program. For these calculations the CTEQ6.6M [23] parametrisation of the parton density functions (PDFs) was used and the renormalisation and factorisation scales were set to the average mass of the sparticles produced in the hard interaction.

For the backgrounds the following Standard Model processes were considered:

- $t\bar{t}$  and single top production: events were generated using the generator MC@NLO [31,32] v3.41. For the evaluation of systematic uncertainties, additional  $t\bar{t}$  samples were generated using the POWHEG [33] and ACERMC [34] programs.
- $W(\rightarrow \ell\nu) + \text{jet}$ ,  $Z/\gamma^*(\rightarrow \ell^+\ell^-) + \text{jet}$  (where  $\ell = e, \mu, \tau$ ) and  $Z(\rightarrow \nu\bar{\nu}) + \text{jet}$  production: events with light and heavy ( $b$ ) flavour jets were generated using the ALPGEN [35] v2.13 program. A generator level cut  $m_{\ell\ell} > 40$  GeV was applied to the  $Z/\gamma^*(\rightarrow \ell^+\ell^-)$  process.
- Jet production via QCD processes (referred to as “QCD background” in the following): events were generated using the PYTHIA [30] v6.4.21 generator. For the evaluation of systematic uncertainties, samples produced with ALPGEN were used.
- Di-boson ( $WW$ ,  $WZ$  and  $ZZ$ ) production: events were generated using ALPGEN, however, compared to the other backgrounds their contribution was found to be negligible, after the application of the selection criteria.

All signal and background samples were generated at  $\sqrt{s} = 7$  TeV using the ATLAS MC09 parameter tune [36], processed with the GEANT4 [37] simulation of the ATLAS detector [38], and then reconstructed and passed through the same analysis chain as the data. For all generators, except for PYTHIA, the HERWIG + JIMMY [19,39] modelling of the parton shower and underlying event was used (v6.510 and v4.31, respectively).

<sup>1</sup> The azimuthal angle  $\phi$  is measured around the beam axis and the polar angle  $\theta$  is the angle from the beam axis. The pseudorapidity is defined as  $\eta = -\ln \tan(\theta/2)$ . The distance  $\Delta R$  in the  $\eta$ - $\phi$  space is defined as  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

**Table 1**

The most important background processes and their production cross sections, multiplied by the relevant branching ratios (BR). Contributions from higher order QCD corrections are included for  $W$  and  $Z$  boson production (NNLO corrections) and for  $t\bar{t}$  production (NLO + NNLL corrections). The inclusive QCD jet cross section is given at leading order (LO). The QCD sample was generated with a cut on the transverse momentum of the partons involved in the hard-scattering process,  $\hat{p}_T$ .

Physics process	$\sigma \cdot \text{BR}$ [nb]	
$W \rightarrow \ell \nu$ (+jets)	$31.4 \pm 1.6$	[24–26]
$Z/\gamma^* \rightarrow \ell^+ \ell^-$ (+jets)	$3.20 \pm 0.16$	[24–26]
$Z \rightarrow \nu \bar{\nu}$ (+jets)	$5.82 \pm 0.29$	[24–26]
$t\bar{t}$	$0.165^{+0.011}_{-0.016}$	[27–29]
Single top	$0.037 \pm 0.002$	[27–29]
Dijet ( $\hat{p}_T > 8$ GeV)	$10.47 \times 10^6$	[30]

For the comparison to data, all background cross sections, except the QCD background cross section, were normalised to the results of higher order QCD calculations. A summary of the relevant cross sections is given in Table 1. For the next-to-next-to-leading order (NNLO)  $W$  and  $Z/\gamma^*$  production cross sections, an uncertainty of  $\pm 5\%$  is assumed [40]. For the  $t\bar{t}$  production cross section, the corresponding uncertainty on the NLO + NNLL (next-to-next-to-leading logarithms) cross section was estimated to be  $+6.5\%$   $-9.5\%$ . For the QCD background, no reliable prediction can be obtained from a leading order Monte Carlo simulation and data-driven methods were used to determine the residual contributions of this background to the selected event samples, as discussed in Section 5.

#### 4. Data and event selection

After the application of beam, detector and data-quality requirements, the data set used for this analysis resulted in a total integrated luminosity of  $35 \text{ pb}^{-1}$ .

For the zero-lepton analysis, events were selected at the trigger level by requiring jets with high transverse momentum. The selection is fully efficient for events containing at least one jet with  $p_T > 120$  GeV. A further trigger level requirement of  $E_T^{\text{miss}} > 25$  GeV was applied [41]. For the one-lepton analysis, the trigger selection was based on single lepton triggers, which retain events if an electron with  $p_T > 15$  GeV or a muon with  $p_T > 13$  GeV is present within the trigger acceptance.

In the data sample selected, jet candidates were reconstructed by using the anti- $k_t$  jet clustering algorithm [42,43] with a distance parameter of  $R = 0.4$ . The inputs to this algorithm are three-dimensional topological calorimeter energy clusters. The jet energies were corrected for inhomogeneities and for the non-compensating nature of the calorimeter by using  $p_T$ - and  $\eta$ -dependent calibration factors. They were determined from Monte Carlo simulation and validated using extensive test-beam measurements and studies of  $pp$  collision data (Ref. [44] and references therein). Only jets with  $p_T > 20$  GeV and within  $|\eta| < 2.5$  were retained. Candidates for  $b$ -jets were identified among jets with  $p_T > 30$  GeV using an algorithm that reconstructs a vertex from all tracks which are displaced from the primary vertex and associated with the jet. The parameters of the algorithm were chosen such that a tagging efficiency of 50% (1%) was achieved for  $b$ -jets (light flavour or gluon jets) in  $t\bar{t}$  events in Monte Carlo simulation [45].

Electron candidates were required to satisfy the ‘medium’ (zero-lepton analysis) or ‘tight’ (one-lepton analysis) selection criteria. Muon candidates were identified either as a match between an extrapolated inner detector track and one or more segments in the muon spectrometer, or by associating an inner detector track to a muon spectrometer track. The combined track parameters were derived from a statistical combination of the two sets of track pa-

rameters. Electrons and muons were required to have  $p_T > 20$  GeV and  $|\eta| < 2.47$  or  $|\eta| < 2.4$ , respectively. Further details on lepton identification can be found in Ref. [40].

The calculation of  $E_T^{\text{miss}}$  is based on the modulus of the vectorial sum of the  $p_T$  of the reconstructed jets (with  $p_T > 20$  GeV and over the full calorimeter coverage  $|\eta| < 4.9$ ), leptons (including non-isolated muons) and the calorimeter clusters not belonging to reconstructed objects.

After object identification, overlaps were resolved. Any jet within a distance  $\Delta R = 0.2$  of a ‘medium’ electron candidate was discarded. The event was rejected if one or more ‘medium’ electrons were identified in the transition region  $1.37 < |\eta| < 1.52$  between the barrel and endcap calorimeters. Any remaining lepton within  $\Delta R = 0.4$  of a jet was discarded.

Events were selected if a reconstructed primary vertex was found associated with five or more tracks, and if they passed basic quality criteria against detector noise and non-collision backgrounds.

In the zero-lepton analysis, events were required to have at least one jet with  $p_T > 120$  GeV, two additional jets with  $p_T > 30$  GeV and  $E_T^{\text{miss}} > 100$  GeV. At least one jet is required to be  $b$ -tagged. Events containing identified ‘medium’ electron or muon candidates were rejected. The effective mass,  $m_{\text{eff}}$ , is defined as the scalar sum of  $E_T^{\text{miss}}$  and the transverse momenta of the highest  $p_T$  jets (up to a maximum of four). Events were required to have  $E_T^{\text{miss}}/m_{\text{eff}} > 0.2$ . In addition, the smallest azimuthal separation between the  $E_T^{\text{miss}}$  direction and the three leading jets,  $\Delta\phi_{\text{min}}$ , was required to be larger than 0.4. The last requirement reduces the amount of QCD background effectively since, in this case,  $E_T^{\text{miss}}$  results from mis-reconstructed jets or from neutrinos emitted along the direction of the jet axis by heavy flavour decays.

In the one-lepton analysis, events were required to have at least one muon or a ‘tight’ electron, two jets with  $p_T > 60$  GeV and  $p_T > 30$  GeV respectively,  $E_T^{\text{miss}} > 80$  GeV and  $m_T > 100$  GeV, where  $m_T$  is the transverse mass constructed using the highest  $p_T$  lepton and  $E_T^{\text{miss}}$ . At least one jet is required to be  $b$ -tagged. The  $m_T$  cut rejects events with a  $W$  boson in the final state.

In both analyses, further cuts on  $m_{\text{eff}}$  were applied to maximise the sensitivity to gluino-mediated production of sbottoms or stops. A threshold on  $m_{\text{eff}}$  at 600 GeV (500 GeV) was chosen for the zero-lepton (one-lepton) analysis. It should be noted that for the one-lepton analysis the transverse momenta of reconstructed leptons are included in the definition of the  $m_{\text{eff}}$ .

The event selection efficiency for each SUSY signal hypothesis was calculated as the sum of the efficiencies for the  $\tilde{g}\tilde{g}$  and  $\tilde{b}_1\tilde{b}_1$  ( $\tilde{t}_1\tilde{t}_1$ ) processes, weighted by their respective NLO cross sections. For the zero-lepton selection, the efficiency varies between 7% and 50% across the  $(m_{\tilde{g}}, m_{\tilde{b}_1})$  plane. The lowest values are found at large  $\Delta m = m_{\tilde{g}} - m_{\tilde{b}_1}$ , where the production of  $\tilde{b}_1\tilde{b}_1$  pairs dominates. As  $\Delta m$  decreases, high efficiency values are found down to  $\Delta m \simeq 20$  GeV. For the one-lepton channel, the efficiency for  $(\tilde{g}, \tilde{t}_1)$ -type SUSY signals varies between 0.4% and 3% across the  $(m_{\tilde{g}}, m_{\tilde{t}_1})$  plane and depends on  $\Delta m = m_{\tilde{g}} - m_{\tilde{t}_1}$  in a similar way to the gluino-sbottom case.

No additional dedicated optimisations were performed for the MSUGRA/CMSSM and SO(10) scenarios. The efficiencies for the zero-lepton (one-lepton) selection for MSUGRA/CMSSM range between 8% (1%) for  $m_{1/2} \simeq 130$  GeV and 23% (12%) for  $m_{1/2} \simeq 340$  GeV, with a smaller dependence on  $m_0$ . For SO(10) models, the highest sensitivity is reached in the zero-lepton analysis, with dominant contributions via  $\tilde{g}\tilde{g}$  production. In this case, the efficiencies vary between 7% and 20% as the gluino mass increases and are generally found to be larger for the DR $\bar{3}$  scenario than for the HS scenario.

## 5. Standard model background estimation

Standard Model processes contribute to the events that survive the selection described in the previous section. The dominant source is  $t\bar{t}$  production due to the presence of jets,  $E_T^{\text{miss}}$  and  $b$ -quarks in the final state.

The QCD background to the zero-lepton final state was estimated by normalising the PYTHIA Monte Carlo prediction to data in a QCD-enriched control region defined by  $\Delta\phi_{\text{min}} < 0.4$ . The Monte Carlo was then used to evaluate the ratio between the number of events in this control region and the signal region ( $\Delta\phi_{\text{min}} > 0.4$ ). In the one-lepton final state the number of QCD multi-jet events was estimated using a matrix method similar to the one described in Ref. [40]. Cuts on the electron and muon identification were relaxed to obtain “loose” control samples that are dominated by QCD jets.

The non-QCD background in the zero-lepton final state was estimated using Monte Carlo simulation, while in the case of the one-lepton final state a data-driven technique is employed. This method exploits the low correlation between  $m_{\text{eff}}$  and  $m_T$ . Four regions were defined: (A)  $40 < m_T < 100$  GeV and  $m_{\text{eff}} < 500$  GeV, (B)  $m_T > 100$  GeV and  $m_{\text{eff}} < 500$  GeV, (C)  $40 < m_T < 100$  GeV and  $m_{\text{eff}} > 500$  GeV and (D)  $m_T > 100$  GeV and  $m_{\text{eff}} > 500$  GeV. Regions A–C are dominated by background from  $t\bar{t}$  and  $W + \text{jet}$  production. Assuming that the variables are uncorrelated, the number of background events in the signal region is given by  $N_D = N_C \times N_B / N_A$ , where  $N_A$ ,  $N_B$ ,  $N_C$  are the numbers of events in the regions A, B and C, respectively. A Monte Carlo simulation was used to validate the method and to establish possible sources of systematic uncertainties. The small number of events in the control regions is the main limitation of the method. It was also checked that a SUSY signal contamination does not bias the estimated background and that any bias is smaller than the systematic uncertainties assigned to the method and on the expected SUSY prediction.

## 6. Systematic uncertainties

Various systematic uncertainties affecting signal and background rates were considered.

For the zero-lepton analysis, the backgrounds from  $t\bar{t}$  and  $W/Z + \text{jet}$  production are taken from Monte Carlo simulation. The total uncertainty on this prediction was estimated to be  $\pm 35\%$  after the final selection. It is dominated by the uncertainty on the jet energy scale (JES) [44], the uncertainty on the theoretical prediction of the background processes and the uncertainty on the determination of the  $b$ -tagging efficiency [45]. The uncertainty on the jet energy scale varies as a function of jet  $p_T$ , and decreases from 6% at 20 GeV to 4% at 100 GeV, with additional contributions taking into account the dependence of the jet response on the jet isolation and flavour. This translates into a  $\pm 25\%$  uncertainty on the absolute prediction of the background from SM processes. Uncertainties on the theoretical cross sections of the background processes (see Section 3), on the modelling of initial and final-state soft gluon radiation and the limited knowledge of the PDFs of the proton lead to uncertainties of  $\pm 20\%$  and  $\pm 25\%$  on the absolute predictions of the  $t\bar{t}$  and the  $W/Z + \text{jet}$  backgrounds, respectively. The uncertainty on the determination of the tagging efficiency for  $b$ -jets,  $c$ -jets and light-jets introduces further uncertainties on the predicted background contributions at the level of  $\pm 12\%$  for  $t\bar{t}$  and  $\pm 25\%$  for  $W/Z + \text{jets}$ . Other uncertainties result from the modelling of additional pile-up interactions ( $\pm 5\%$ ) and of the trigger efficiency ( $\pm 3\%$ ) in the Monte Carlo simulation. For the QCD background estimation, the uncertainty is dominated by the limited number of Monte Carlo events available for the zero-lepton analysis.

For the one-lepton analysis, where a data-driven technique was employed, the small event number in the control regions was the dominant uncertainty ( $\pm 25\%$ ). Residual uncertainties associated to the method due to the JES,  $b$ -tagging, lepton identification and theoretical predictions of the relative contributions of  $W$  and  $t\bar{t}$  backgrounds were studied using Monte Carlo simulation and estimated to be at the level of  $\pm 8\%$ .

For the SUSY signal processes, various sources of uncertainties affect the theoretical NLO cross sections. Variations of the renormalisation and factorisation scales by a factor of two result in uncertainties of  $\pm 16\%$  for  $\tilde{g}\tilde{g}$  production and  $\pm 30\%$  ( $\pm 27\%$ ) for  $\tilde{b}_1\tilde{b}_1$  ( $\tilde{t}_1\tilde{t}_1$ ) pair production, almost independently of the sparticle mass and the SUSY model. Uncertainties for  $\tilde{q}\tilde{q}$  and  $\tilde{q}\tilde{g}$  production, relevant in MSUGRA/CMSSM scenarios, were estimated to be at the level of  $\pm 10\%$  and  $\pm 15\%$ , respectively.

The number of predicted signal events is also affected by the PDF uncertainties, estimated using the CTEQ 6.6M PDF error eigenvector sets at the 90% C.L. limit, and rescaled by  $1/1.645$ . The relative uncertainties on the  $\tilde{g}\tilde{g}$  ( $\tilde{b}_1\tilde{b}_1$ ,  $\tilde{t}_1\tilde{t}_1$ ) cross sections were estimated to be in the range from  $\pm 11\%$  to  $\pm 25\%$  ( $\pm 7\%$  to  $\pm 16\%$ ) for the  $\tilde{g}\tilde{g}$  ( $\tilde{b}_1\tilde{b}_1$ ,  $\tilde{t}_1\tilde{t}_1$ ) processes, depending on the gluino (sbottom, stop) masses. For first and second generation squark-pair and associated gluino-squark production, the uncertainty on the PDFs varies between  $\pm 5\%$  and  $\pm 15\%$  as the squark masses increase. The impact of detector related uncertainties, such as the JES and  $b$ -tagging, on the signal event yields depends on the masses of the most copiously produced sparticles. The total uncertainty varies between  $\pm 25\%$  and  $\pm 10\%$  as the gluino/squark masses increase from 300 GeV to 1 TeV, across the different scenarios, and it is dominated by the JES and the  $b$ -tagging uncertainty for low and high mass sparticles, respectively.

Finally, an additional  $\pm 11\%$  uncertainty on the quoted total integrated luminosity was taken into account.

## 7. Results

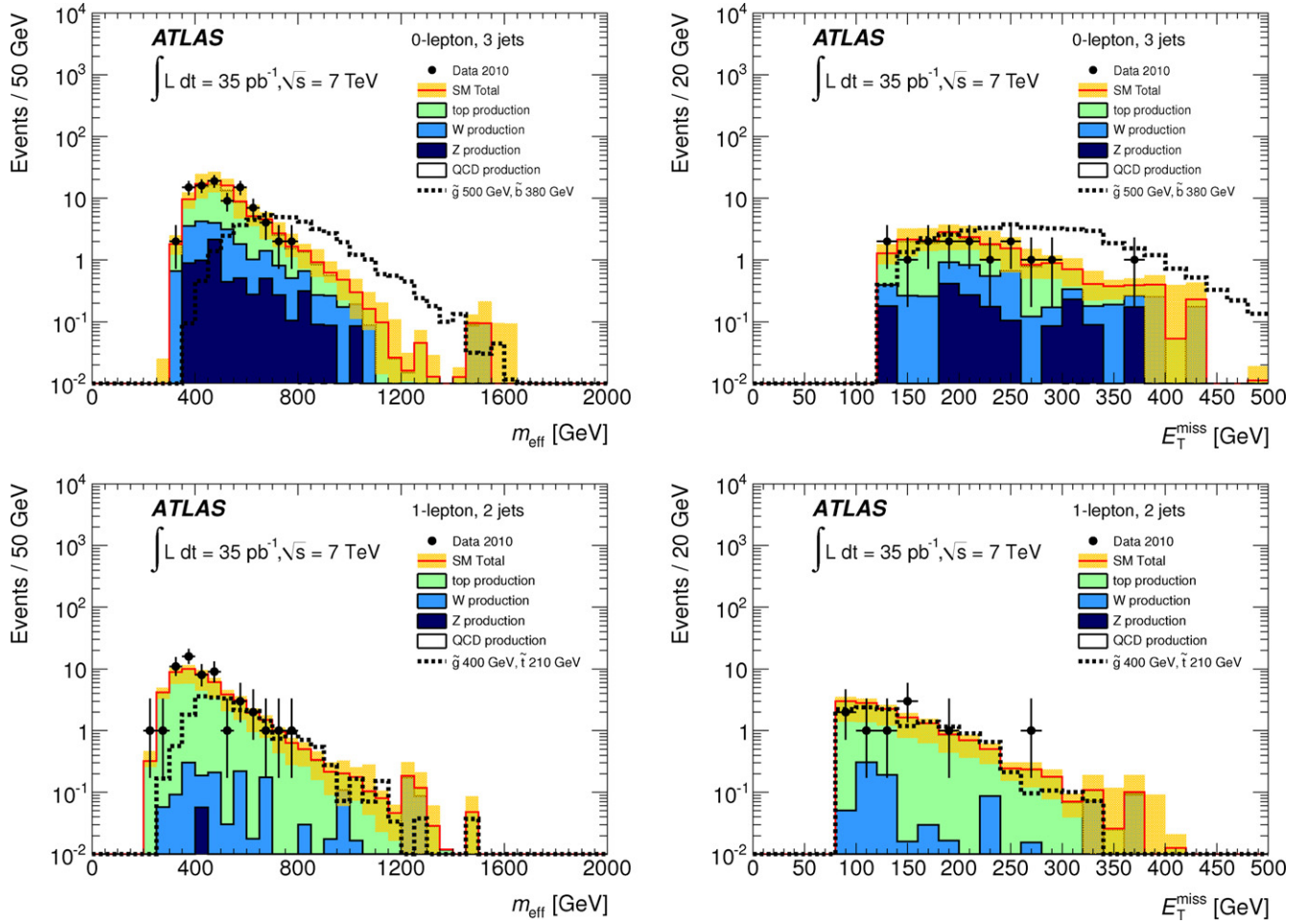
In Fig. 1 the distributions of  $m_{\text{eff}}$  and of  $E_T^{\text{miss}}$  are shown for the two analyses. For the  $E_T^{\text{miss}}$  distributions all cuts described in Section 4 are applied. The  $m_{\text{eff}}$  distributions are shown after the application of all cuts, except for the  $m_{\text{eff}}$  cut.

The expectations from Standard Model background processes are superimposed. For illustration, the figures also include the distributions expected for SUSY signals. For the zero-lepton channel, a scenario with  $m_{\tilde{g}} = 500$  GeV and  $m_{\tilde{b}_1} = 380$  GeV is chosen, while for the one-lepton channel the relevant masses are  $m_{\tilde{g}} = 400$  GeV and  $m_{\tilde{t}_1} = 210$  GeV. In Table 2, the observed number of events and the predictions for contributions from Standard Model processes are presented. For both analyses, the data are in agreement with the Standard Model predictions, within uncertainties.

The results are translated into 95% C.L. upper limits on contributions from new physics. Limits were derived using a profile likelihood ratio [46,47],  $\Lambda(s)$ , where the likelihood function of the fit was written as  $L(n|s, b, \theta) = P_s \times C_{\text{Syst}}$ ;  $n$  represents the number of observed events in data,  $s$  is the SUSY signal under consideration,  $b$  is the background, and  $\theta$  represents the systematic uncertainties. The  $P_s$  function is a Poisson-probability distribution for event counts in the defined signal region and  $C_{\text{Syst}}$  represents the constraints on systematic uncertainties, which are treated as nuisance parameters with a Gaussian probability density function and correlated when appropriate. The exclusion  $p$ -values are obtained from the test statistic  $\Lambda(s)$  using pseudo-experiments. One-sided upper limits are set with the power-constrained limits procedure [48].

Upper limits at 95% C.L. on the number of signal events in the signal regions are obtained independently of new physics models for the zero- and one-lepton final states. These numbers are





**Fig. 1.** Distributions of the effective mass,  $m_{\text{eff}}$  (left) and the  $E_T^{\text{miss}}$  (right) for data and for the expectations from Standard Model processes after the baseline selections in the zero-lepton (top) and one-lepton channel (bottom). The data correspond to an integrated luminosity of  $35 \text{ pb}^{-1}$ . Black vertical bars show the statistical uncertainty of the data. The yellow band shows the full systematic uncertainty on the SM expectation. The  $E_T^{\text{miss}}$  distributions are shown after a cut on  $m_{\text{eff}}$  at 600 GeV (zero-lepton) and 500 GeV (one-lepton). For illustration, the distributions for one reference SUSY signal, relevant for each channel, are superimposed.

**Table 2**

Summary of the expected and observed event yields. The QCD prediction for the zero-lepton channel is based on the semi-data-driven method described in the text. For the one-lepton channel, the results for both the Monte Carlo and the data-driven approach are given. Since the data-driven technique does not distinguish between top and W/Z backgrounds the total background estimate is shown in the top row. The errors are systematic for the expected Monte Carlo prediction and statistical for the data-driven technique.

	0-lepton	1-lepton Monte Carlo	1-lepton data-driven
$t\bar{t}$ and single top	$12.2 \pm 5.0$	$12.3 \pm 4.0$	$14.7 \pm 3.7$
W and Z	$6.0 \pm 2.6$	$0.8 \pm 0.4$	–
QCD	$1.4 \pm 1.0$	$0.4 \pm 0.4$	$0^{+0.4}_{-0.0}$
Total SM	$19.6 \pm 6.9$	$13.5 \pm 4.1$	$14.7 \pm 3.7$
Data	15	9	9

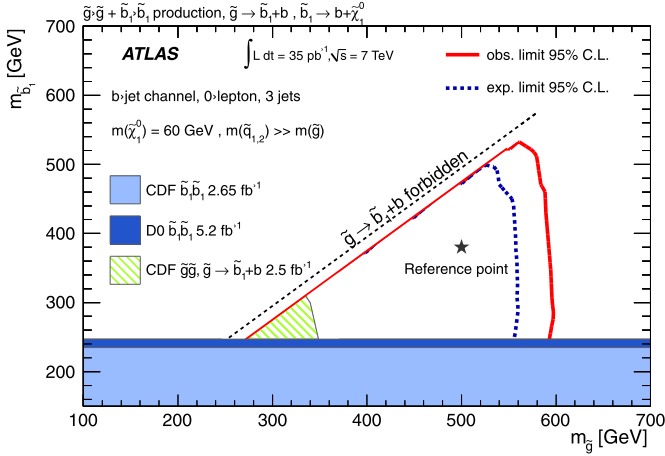
11.1 and 5.2, respectively, and correspond to 95% C.L. upper limits on effective cross sections for new processes of 0.32 pb and 0.15 pb for the zero- and one-lepton channel, respectively. These upper limits include the  $\pm 11\%$  uncertainty on the quoted total integrated luminosity.

These results can be interpreted in terms of 95% C.L. exclusion limits in several SUSY scenarios. In Fig. 2 the observed and expected exclusion regions are shown in the  $(m_{\tilde{g}}, m_{\tilde{b}_1})$  plane, for the hypothesis that the lightest squark  $\tilde{b}_1$  is produced via gluino-

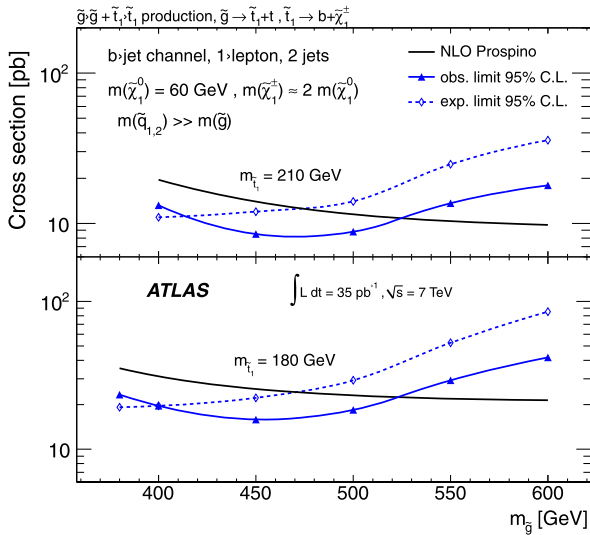
mediated or direct pair production and decays exclusively via  $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ . The zero-lepton channel was considered for this model and the largest acceptance was found for  $\tilde{g}\tilde{g}$  production. The limits do not strongly depend on the neutralino mass assumption as long as  $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$  is larger than 250–300 GeV, due to the harsh kinematic cuts. Gluino masses below 590 GeV are excluded for sbottom masses up to 500 GeV. These limits depend weakly – via the dependence of the production cross section for  $\tilde{g}\tilde{g}$  production – on the masses of the first and second generation squarks,  $\tilde{q}_{1,2}$ . Variations of these masses in the range between  $\sim 3 \text{ TeV}$  and  $2 \cdot m_{\tilde{g}}$  reduce the excluded mass region by less than 20 GeV.

The zero-lepton analysis was also employed to extract limits on the gluino mass in the two SO(10) scenarios, DR3 and HS. Gluino masses below 500 GeV are excluded for the DR3 models considered, where  $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$  decays dominate. A lower sensitivity ( $m_{\tilde{g}} < 420 \text{ GeV}$ ) was found for the HS model, where larger branching ratios of  $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_2^0$  are expected and the efficiency of the selection is reduced with respect to the DR3 case.

The results of the one-lepton analysis were interpreted as exclusion limits on the  $(m_{\tilde{g}}, m_{\tilde{t}_1})$  plane in the hypothesis that the lightest  $\tilde{t}_1$  is produced via gluino-mediated or direct pair production. Stop masses above 130 GeV are considered, and  $\tilde{t}_1$  is assumed to decay exclusively via  $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ . In Fig. 3 the observed and expected exclusion limits are shown as a function of  $m_{\tilde{g}}$  for



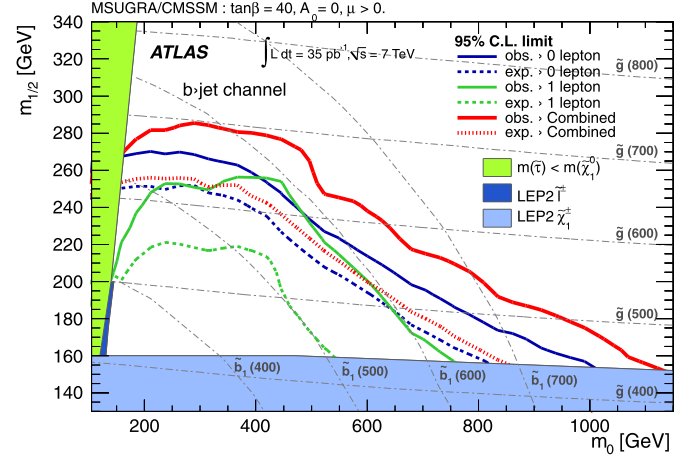
**Fig. 2.** Observed and expected 95% C.L. exclusion limits, as obtained with the zero-lepton channel, in the  $(m_{\tilde{g}}, m_{\tilde{b}_1})$  plane. The neutralino mass is assumed to be 60 GeV and the NLO cross sections are calculated using PROSPINO in the hypothesis of  $m_{\tilde{q}_{1,2}} \gg m_{\tilde{g}}$ . The result is compared to previous results from CDF searches which assume the same gluino-sbottom decays hypotheses, a neutralino mass of 60 GeV and  $m_{\tilde{q}_{1,2}} = 500$  GeV ( $\gg m_{\tilde{g}}$  for the Tevatron kinematic range). Exclusion limits from the CDF and D0 experiments on direct sbottom pair production [8,9] are also reported.



**Fig. 3.** Observed and expected 95% C.L. upper limits, as obtained with the one-lepton analysis, on the gluino-mediated and stop pair production cross section as a function of the gluino mass for two assumed values of the stop mass and  $\text{BR}(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm) = 1$ . The chargino is assumed to have twice the mass of the neutralino ( $= 60$  GeV) and NLO cross sections are calculated using PROSPINO in the hypothesis of  $m_{\tilde{q}_{1,2}} \gg m_{\tilde{g}}$ . Theoretical uncertainties on the NLO cross sections are included in the limit calculation.

two representative values of the stop mass. Gluino masses below 520 GeV are excluded for stop masses in the range between 130 and 300 GeV.

Finally, the results of both analyses were used to calculate 95% C.L. exclusion limits in the MSUGRA/CMSSM framework with large  $\tan\beta$ . Fig. 4 shows the observed and expected limits in the  $(m_0, m_{1/2})$  plane, assuming  $\tan\beta = 40$ , and fixing  $\mu > 0$  and  $A_0 = 0$ . The largest sensitivity is found for the zero-lepton analysis. The combination of the two analyses, which takes account of correlations between systematic uncertainties of the two channels, is also shown. Sbottom and stop masses below 550 GeV and 470 GeV are excluded across the plane, respectively. Due to the MSUGRA/CMSSM constraints, this interpretation is also sensitive



**Fig. 4.** Observed and expected 95% C.L. exclusion limits as obtained from the zero- and one-lepton analyses, separately and combined, on MSUGRA/CMSSM scenario with  $\tan\beta = 40$ ,  $A_0 = 0$ ,  $\mu > 0$ . The light-grey dashed lines are the iso-mass curves for gluinos and sbottom – stop masses are 15% lower than sbottom masses, across the  $(m_0, m_{1/2})$  parameter space. The results are compared to previous limits from the LEP experiments [14].

to first and second generation squarks. From the present analysis, masses of these squarks below 600 GeV are excluded for  $m_{\tilde{g}} \simeq m_{\tilde{q}}$ . Gluino masses below 500 GeV are excluded for the  $m_0$  range between 100 GeV and 1 TeV, independently on the squark masses. Changing the  $A_0$  value from 0 to  $-500$  GeV lead to significant variations in third generation squark mixing. Across the  $(m_0, m_{1/2})$  parameter space, sbottom and stop masses decrease by about 10% and 30%, respectively, if  $A_0$  is changed from 0 to  $-500$  GeV. The exclusion region of the one-lepton analysis, mostly sensitive to stop final states, extends the zero-lepton reach by about 20 GeV in  $m_{1/2}$  for  $m_0 < 600$  GeV.

## 8. Conclusions

The ATLAS Collaboration has presented a first search for supersymmetry in final states with missing transverse momentum and at least one  $b$ -jet candidate in proton–proton collisions at 7 TeV. The results are based on data corresponding to an integrated luminosity of  $35 \text{ pb}^{-1}$  collected during 2010. These searches are sensitive to the gluino-mediated and direct production of sbottoms and stops, the supersymmetric partners of the third generation quarks, which, due to mixing effects, might be the lightest squarks.

Since no excess above the expectations from Standard Model processes was found, the results are used to exclude parameter regions in various  $R$ -parity conserving SUSY models. Under the assumption that the lightest squark  $\tilde{b}_1$  is produced via gluino-mediated processes or direct pair production and decays exclusively via  $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ , gluino masses below 590 GeV are excluded with 95% C.L. up to sbottom masses of 500 GeV. Alternatively, assuming that  $\tilde{t}_1$  is the lightest squark and the gluino decays exclusively via  $\tilde{g} \rightarrow \tilde{t}_1 t$ , and  $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ , gluino masses below 520 GeV are excluded for stop masses in the range between 130 and 300 GeV.

In specific models based on the gauge group  $\text{SO}(10)$ , gluinos with masses below 500 GeV and 420 GeV are excluded for the DR3 and HS models, respectively.

In an MSUGRA/CMSSM framework with large  $\tan\beta$ , a significant region in the  $(m_0, m_{1/2})$  plane can be excluded. For the parameters  $\tan\beta = 40$ ,  $A_0 = 0$  and  $\mu > 0$ , sbottom masses below 550 GeV and stop masses below 470 GeV are excluded with 95% C.L. Gluino

masses below 500 GeV are excluded for the  $m_0$  range between 100 GeV and 1 TeV, independently on the squark masses.

These analyses improve significantly on the regions of SUSY parameter space excluded by previous experiments that searched for similar scenarios.

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 V. Cavasinni<sup>122a,122b</sup>, A. Cazzato<sup>72a,72b</sup>, F. Ceradini<sup>134a,134b</sup>, A.S. Cerqueira<sup>23a</sup>, A. Cerri<sup>29</sup>, L. Cerrito<sup>75</sup>,  
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